Title: Probing Fundamental Physics and the Early Universe by Detecting Gravitational Waves

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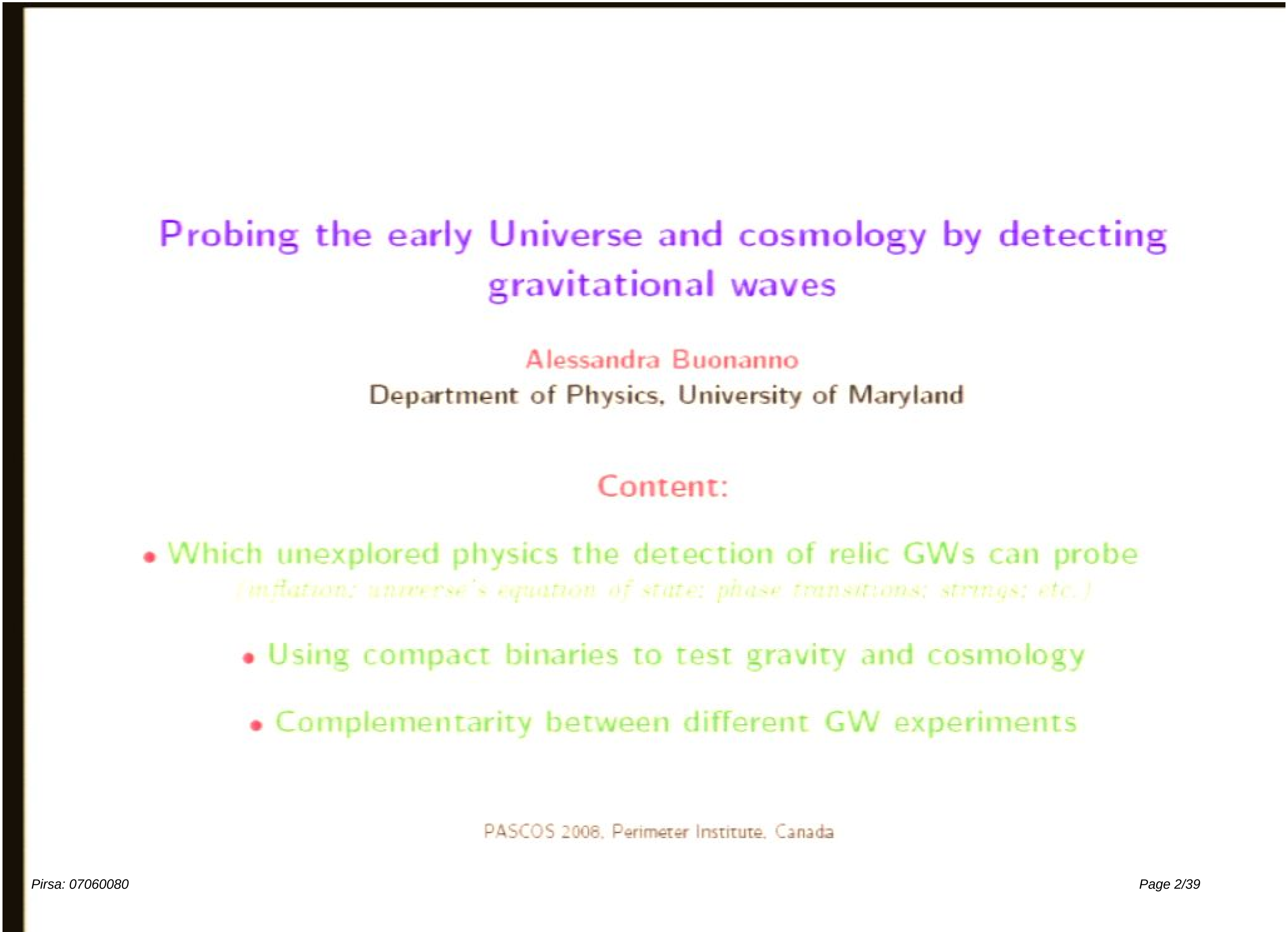
Abstract:



Probing the early Universe and cosmology by detecting gravitational waves

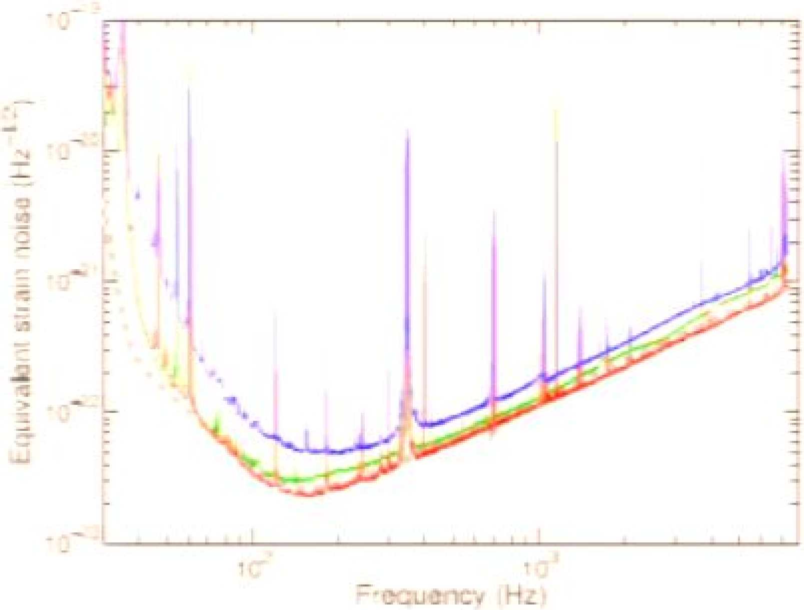
Alessandra Buonanno
Department of Physics, University of Maryland

Content:

- Which unexplored physics the detection of relic GWs can probe
  (inflation; universe's equation of state; phase transitions; strings; etc.)
- Using compact binaries to test gravity and cosmology
- Complementarity between different GW experiments

PASCOS 2006, Perimeter Institute, Canada

Current and future GW detectors



[Abbott et al. (LIGO Scientific Collaboration) 07]

[Whelean for LIGO Scientific Collaboration, AAS 08]

- S4-run data provided the current upper limit: $h_0^2\,\Omega_{\rm GW} < 6.5 \times 10^{-5}$ over frequency range $51-151\mathrm{Hz}$ assuming freq-independent spectrum
- S5-run data at design sensitivity are under investigation. Preliminary upper limit: $h_0^2\,\Omega_{\rm GW} < 9.0 \times 10^{-6}$

- Advanced detectors: Enhanced LIGO, Virgo+; Adv. LIGO and Virgo; Third Gen. Det.
- Preliminary designs of GW detectors at very high frequency ($\sim \mathrm{MHz}$)
- Space-based laser interferometer (LISA) within the next 15 (?) years

Disclosing the *primordial dark age* of the Universe

- What is currently measured?

– $\rho_\gamma, \rho_{\rm m}, \rho_{\rm b}, (n_{\rm b} - n_{\bar{\rm b}})/s, \rho_\Lambda \cdots$

– $(\Delta^2_{\mathcal{R}})_{|k_\bullet}, n_s, (d\log\Delta^2_{\mathcal{R}}/d\log k)_{|k_\bullet}$

- Particles as probes

γ — free-streaming at $\sim 1\mathrm{eV}$

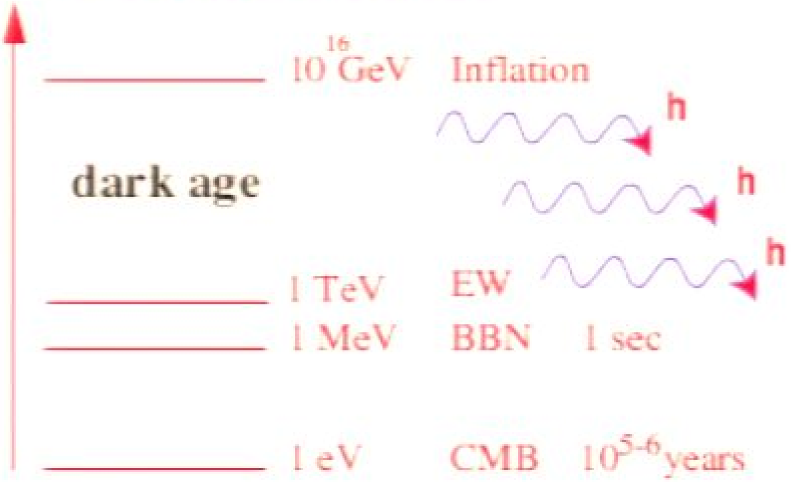
ν — streaming at $\sim 1\mathrm{MeV}$

h — streaming since end of inflation

$\sim 10^7\mathrm{TeV}$

$$ds^2 = a^2\left[-d\tau^2 + (\delta_{ij} + h_{ij})\,dx^i\,dx^j\right]$$

Very *clean* cosmological probes



- What can we probe by detecting primordial GWs?
  - Universe equation of state
  - end of inflation
  - phase transitions
  - cosmic strings

Characteristic intensity and frequency of relic gravitational waves

- The intensity

Tensor power spectrum: $\Delta_h^2(k\tau) \equiv \frac{d\langle 0|h_{ij}^2|0\rangle}{d\log k} \propto k^3\,|h_k(\tau)|^2$

GW energy spectrum: $\Omega_{\rm GW}(k,\tau) \equiv \frac{1}{\rho_c(\tau)}\,\frac{d\langle 0|\rho_{\rm GW}(\tau)|0\rangle}{d\log k} \propto \frac{k^2\,\Delta_h^2(k\tau)}{a^2(\tau)\,H^2(\tau)}$

- The phenomenological bounds
- Features determining typical GW frequencies: the *dynamics* of production mechanism which is model dependent, and the *kinematics*, i.e. the redshift from the production era

Suppose a graviton is produced at time t_* with frequency f_* during RD or MD era

$$f_0 = f_*\, a_*/a_0, \quad g\, a^3\, T^3 = \text{const.}, \quad 1/f_* = \lambda_* = \epsilon\, H_*^{-1}$$

$$f_0 \simeq 10^{-7}\,\frac{1}{\epsilon}\,\left(\frac{T_*}{1\,\text{GeV}}\right)\,\left(\frac{g_*}{100}\right)^{1/6}\ \text{Hz}$$

[Kamionkowski, Kosowski & Turner 94; Maggiore 00]

Phenomenological bounds

- BBN bound

$\int h_0^2\,\Omega_{\rm GW}(f)\,d\log f \leq$
$5.6 \times 10^{-6}\,(N_\nu - 3)$

[Copi, Schramm and Turner 97]

- CMB bound

[Smith et al. 06]

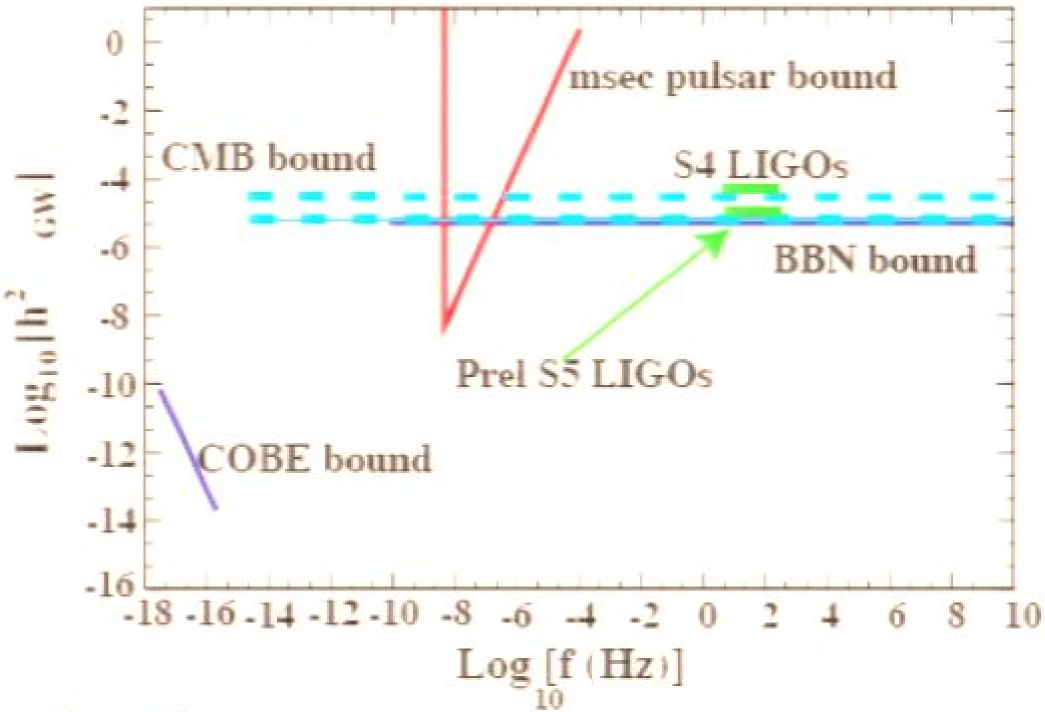
- COBE bound

$h_0^2\,\Omega_{\rm GW}(f) \leq 7 \times 10^{-11}\,\left(\frac{H_0}{f}\right)^2$
$H_0 \leq f \leq 10^{-16}$ Hz

- msec pulsar bound

$h_0^2\,\Omega_{\rm GW}(f) \leq 4.8 \times 10^{-9}\left(\frac{f}{f_\circ}\right)^2$
$f > f_\circ \equiv 4.4 \times 10^{-9}$ Hz

[Thorsett & Dewey 96; see also Jenet et al. 06]



Production of GWs from inflation: exiting and re-entering the *horizon*

[Grishchuk 74; Starobinsky 79]

Introducing "canonical field" $\psi_k(\tau) = a\, h_k(\tau)$:

$$\psi_k'' + \left[k^2 - U(\tau)\right]\, \psi_k = 0 \qquad U(\tau) = \frac{a''}{a}$$

- If $k^2 \gg |U(\tau)| \Rightarrow \lambda_{\rm phys} \ll H^{-1}$

$\Rightarrow$ the mode is inside the Hubble radius

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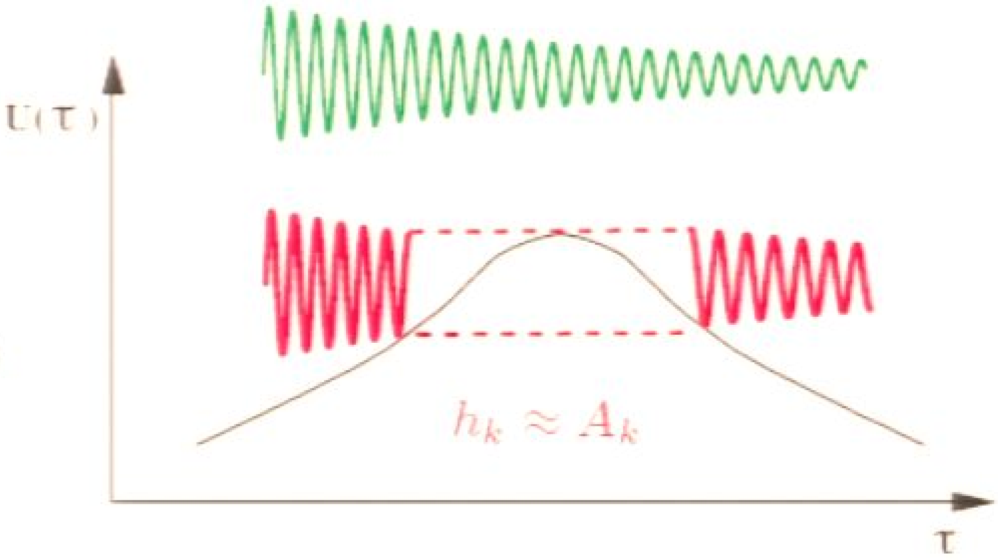
$$h_k = \frac{1}{\sqrt{2k}}\, \frac{1}{a}\, e^{-ik\tau}$$



Stochastic GW background from inflation

[Grishchuk 74; Starobinsky 79]

In *slow-roll* inflation Hubble radius slightly increases in time

- $\Delta_h^2(k) \approx 8 \left(\frac{H_\bullet}{2\pi M_{\rm pl}}\right)^2 \quad \Delta_{\mathcal{R}}^2(k) \approx \frac{1}{\epsilon_\bullet} \left(\frac{H_\bullet}{2\pi M_{\rm pl}}\right)^2$

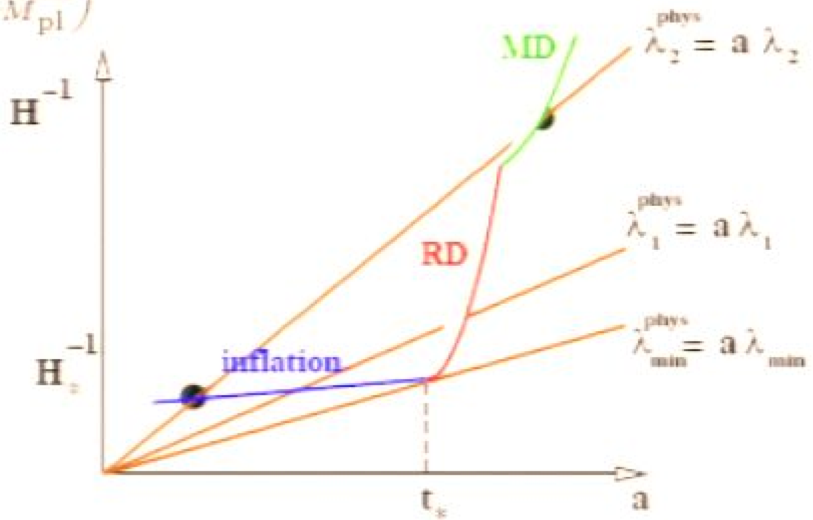
  $\Delta_h^2(k;\tau) = \underbrace{\mathcal{T}_h(k;\tau)}_{\text{transfer function}} \quad \Delta_h^2(k;\tau_i)$

- $r(k) \equiv \Delta_h^2(k)/\Delta_{\mathcal{R}}^2(k) = 16\epsilon_\bullet$

  $\epsilon \propto d\log V/d\log N$

  $\Omega_{\rm GW}(f) \sim H_\bullet^2\, f^{n_T} \quad n_T = -r/8$

  cutoff frequency $f_*^{\rm max} \sim H_*/2\pi$



Inflation: $H^{-1} \simeq \text{const.}$

RD: $H^{-1} \propto a^2$

MD: $H^{-1} \propto a^{3/2}$

- **GWB carries information on two moments of cosmic history: when k *exit* the horizon and *re-entered* it**

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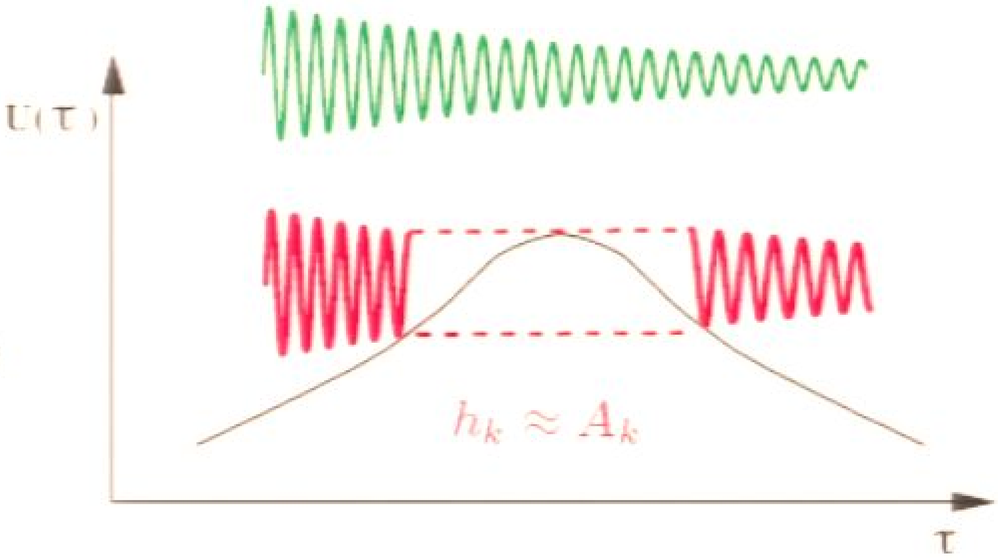

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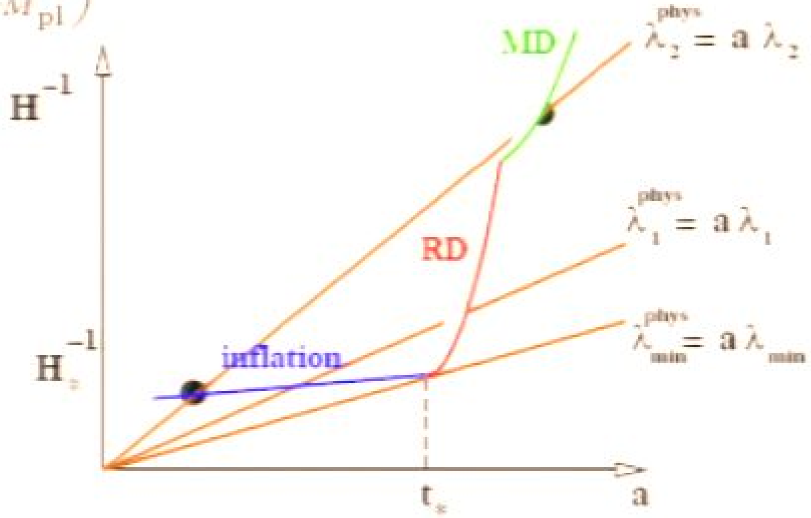

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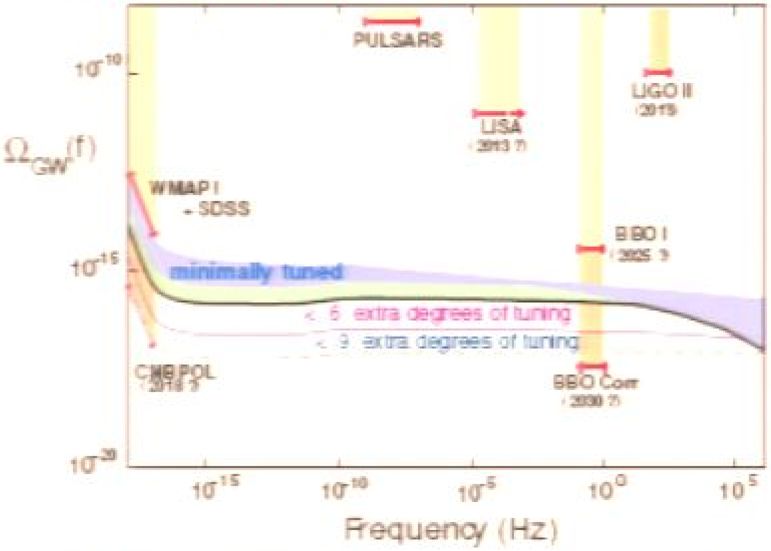
Transfer function and predictions from slow-roll inflationary models

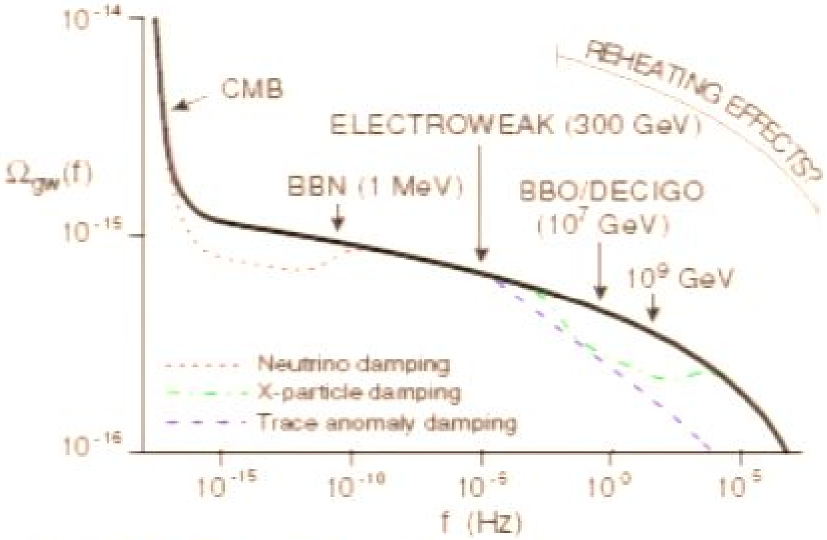


- CMB sensitive to long wavelengths that *re-entered* at low temperature (after BBN)
- GW IFOs sensitive to short wavelengths that *re-entered* at high temperature

[see also Ungarelli et al. 05; Smith et al. 06]

[Efstathiou et al.; Kudoh et al.; Watanabe et al. 06]

[Boyle, Steinhardt & Turok 05]



- Transfer function includes

— dark energy with time dependent eq of state

— tensor anisotropic stress due to free-streaming of relativistic particle in early Universe

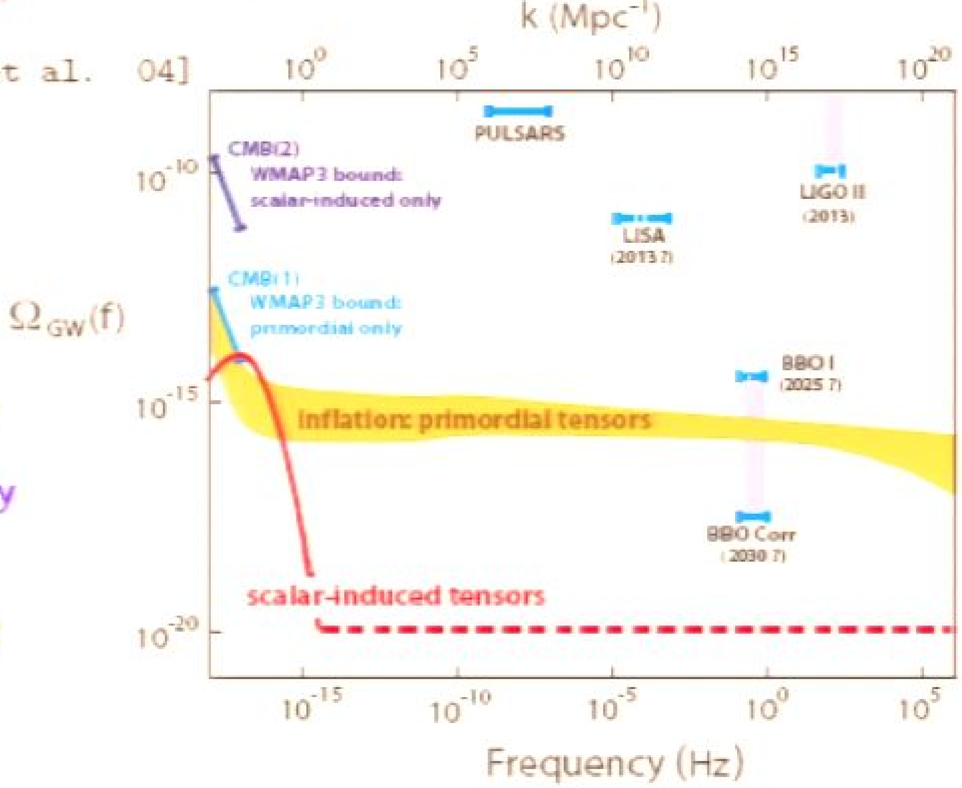
[Weinberg 03]

Stochastic GW background induced by primordial scalar perturbations

[Matarrese et al. 93; Mollerach et al. 04]

[Ananda et al. 07]

- Independent on inflation
- Dependent on observed scalar spectrum and general relativity
- Model-independent lower limit on GW spectrum



[Baumann, Steinhardt, Takahashi & Ichiki 07]

Dependence of $\Omega_{\rm GW}$ on equation of state at *exit* and *re-entry*

[Boyle & AB 07]

$$\Omega^{\rm gw}(f) = \left[A_1\, A_2^{\tilde{\alpha}(f)}\, A_3^{n_t(f)}\right] r, \qquad f_{\rm BBN} < f < f_{\rm end}$$

$$\Omega^{\rm gw}(f) \propto f^{\tilde{\alpha}(f)+n_t(f)}$$

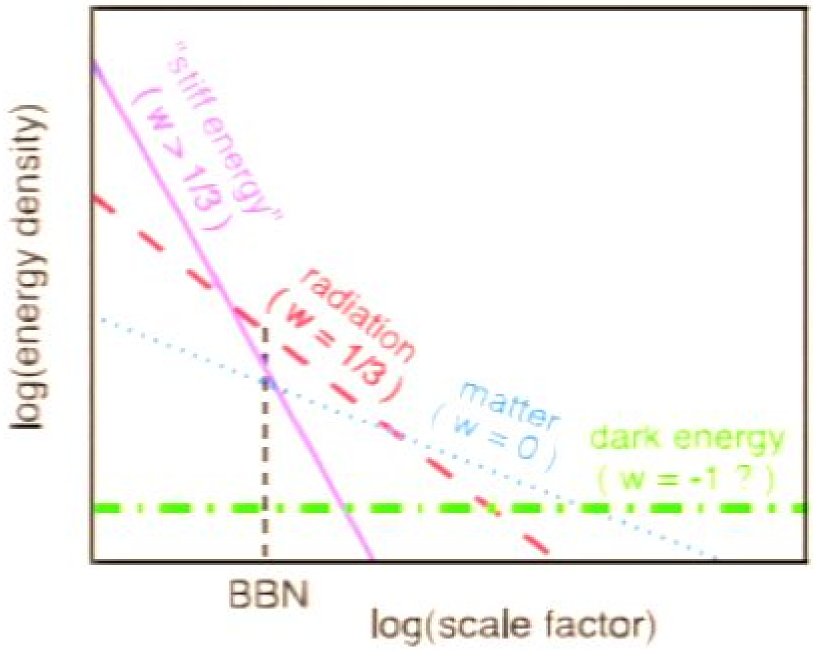
- $\tilde{\alpha}(f) \equiv 2\left(\frac{3\tilde{w}(f)-1}{3\tilde{w}(f)+1}\right) \qquad \tilde{w}(f) \equiv \frac{1}{\ln(a_{\rm BBN}/a_k)}\int_{a_k}^{a_{\rm BBN}} w(a)\frac{da}{a}$

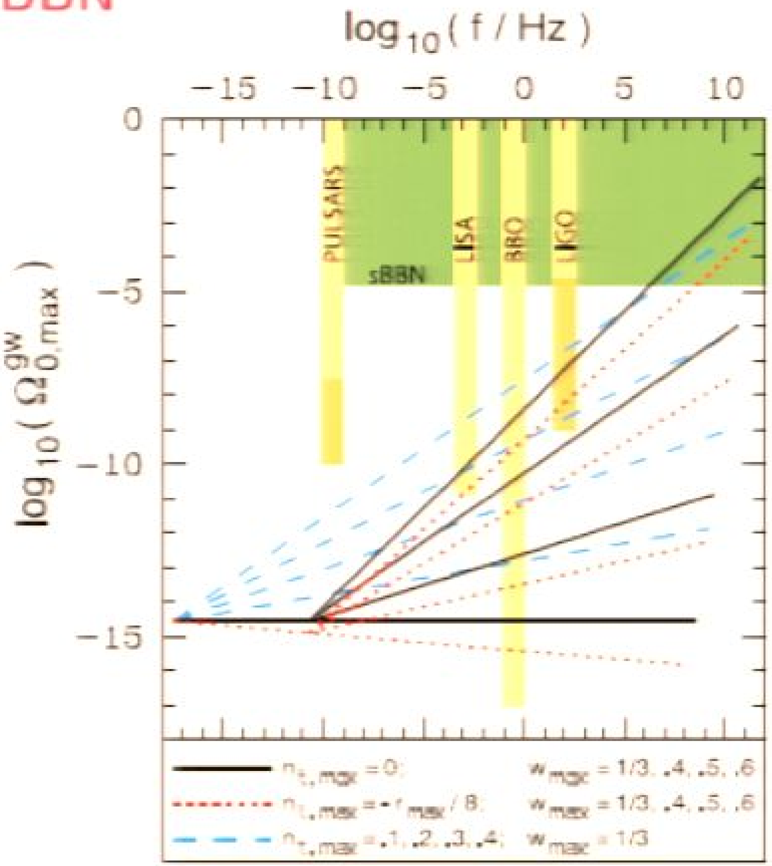
where $w(a) = p(a)/\rho(a)$ **is the equation-of-state and** $k/a_0 = 2\pi f$

- $n_t(f) \equiv \frac{1}{\ln(k/k_{\rm cmb})}\int_{k_{\rm cmb}}^{k} n_t(k')\frac{dk'}{k'} \qquad n_t(k) = 3 - 3\left|\frac{1-w_{\rm exit}(k)}{1+3\,w_{\rm exit}(k)}\right|$

Constraining (or detect) the presence of a *stiff* energy component prior to BBN

[Boyle & AB 07]





- $\rho \propto a^{-3(1+w)} \Rightarrow$ the lower the w, the slower it dilutes
- In *standard* picture $w \leq 1/3$, but ... [Grishchuk 75; Peebles & Vilenkin 98; Sahni et al. 99]

Implications from combining CMB and BBN constraints

[Boyle & AB 07]

$$\int_{f_{\rm BBN}}^{f_{\rm end}} \Omega^{\rm gw}(f)\,\frac{df}{f} \leq 1.5 \times 10^{-5}$$

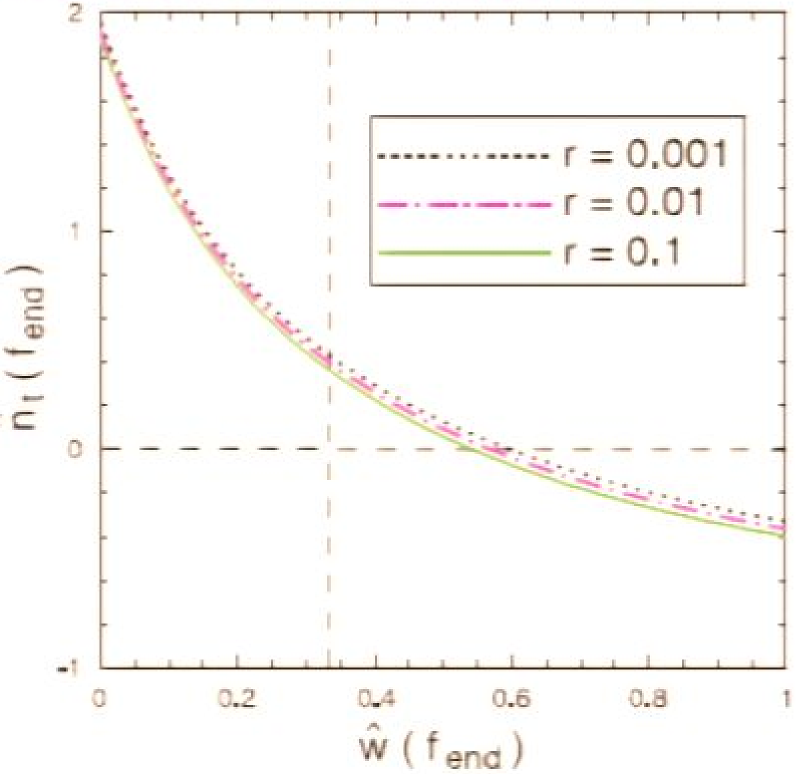
$$n_{t,\rm max}(f) = -\frac{\ln\left[r\,A_1 A_2^{\hat{\alpha}(f)}/\Omega^{\rm gw}_{\rm max}(f)\right]}{\ln[A_3]}$$

$$\hat{\alpha}(f) = 2\left(\frac{3\,\hat{w}(f)-1}{3\,\hat{w}(f)+1}\right)$$

If CMB experiments detect a non-zero r

$\Rightarrow$ upper bound on equation-of-state w

during dark age!



$$\hat{n}_t \approx 0 \Rightarrow \hat{w}(f_{\rm end}) \lesssim \{0.54, 0.57, 0.6\}$$

$$\hat{w}_t \approx 1/3 \Rightarrow \hat{n}(f_{\rm end}) \lesssim \{0.36, 0.40, 0.43\}$$

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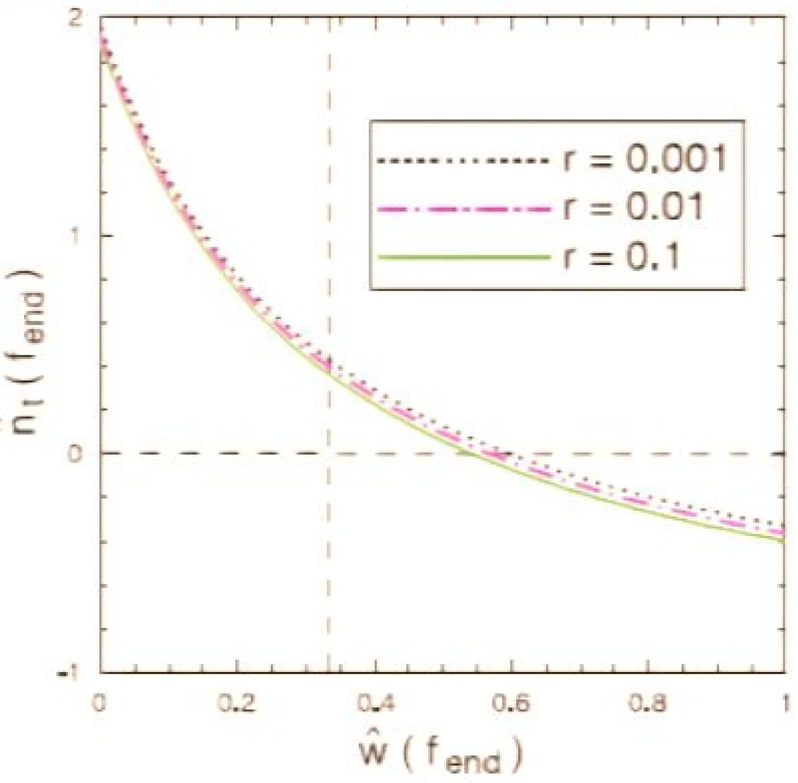

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Probing how inflation ended

- GWs produced during preheating

[Khlebnikov & Thachev 97]

$$v_{ij}(\mathbf{k}) + \left(k^2 - \frac{a''}{a}\right) v_{ij}(\mathbf{k}) = 16\pi G\, a^3\, \Pi^{\rm TT}_{ij}(\mathbf{k})$$

– Highly non-thermal phase during which inflaton pumps energy to coupled-field momentum modes

– Transient density inhomogeneities ⇒ GW production

– The GW spectrum peaks at a frequency fixed by energy scale at the end of inflation

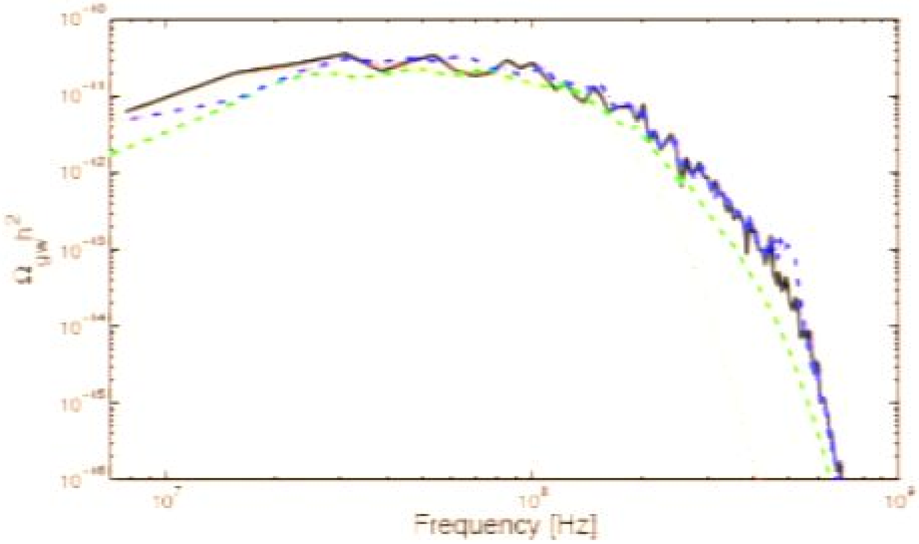
$$f^{\rm peak} \sim \frac{4\times 10^{10}}{R_\star\, \rho_{\rm p}^{1/4}}\,{\rm Hz} \qquad h_0^2\,\Omega_{\rm GW}^{\rm peak} \sim 10^{-6}\,(R_\star\, H_{\rm p})^2$$

$R_\star$ — scale of inhomogeneity

[Dufaux et al. 07]

GW spectrum from preheating in chaotic and hybrid inflation

Chaotic inflation



Hybrid inflation ($V_{\rm infl} = \lambda\, v^4/4$)

[Dufaux et al. 07]

- "High" inflaton velocity

$$f^{\rm peak} \sim \lambda^{1/4} \times 10^{10} {\rm Hz}$$

$$h_0^2\, \Omega_{\rm GW}^{\rm peak} \sim 10^{-6} \left(\frac{v}{M_{\rm pl}}\right)^2$$

- "Low" inflaton velocity

$$f^{\rm peak} \sim \lambda^{3/4} \times 10^{10} {\rm Hz}$$

$$h_0^2\, \Omega_{\rm GW}^{\rm peak} \sim 10^{-6}\, \frac{1}{\lambda} \left(\frac{v}{M_{\rm pl}}\right)^2$$

[Easther et al. 06-07; Dufaux et al. 07; Garcia-Bellido et al. 07; Price & Siemens 08]

- First examples of laser interferometers GW detectors operating at $\sim {\rm MHz}$

  [Kawamura's group 07] (note that $f\, S_h \sim \Omega_{\rm gw}/10^{36}/(f/{\rm Hz})^2$)

GW spectrum from preheating in chaotic and hybrid inflation [continued]

Could the signal be observed by LIGOs?

- "Low" inflaton velocity

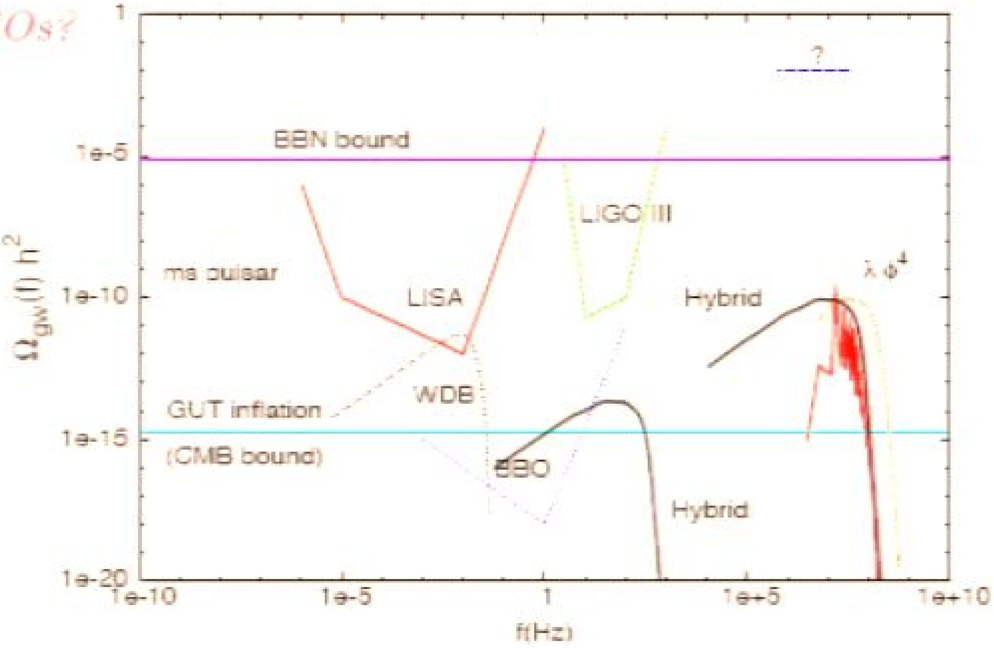
  [Dufaux et al. 07]

  $\lambda < 10^{-11}$

  $f^{\rm peak} \sim 50{\rm Hz}$

  $h_0^2\,\Omega_{\rm GW}^{\rm peak} \sim 10^{-6}$

  Just an estimate but tuning seems necessary



[Easther et al. 06-07; Dufaux et al. 07; Garcia-Bellido et al. 07; Price & Siemens 08]

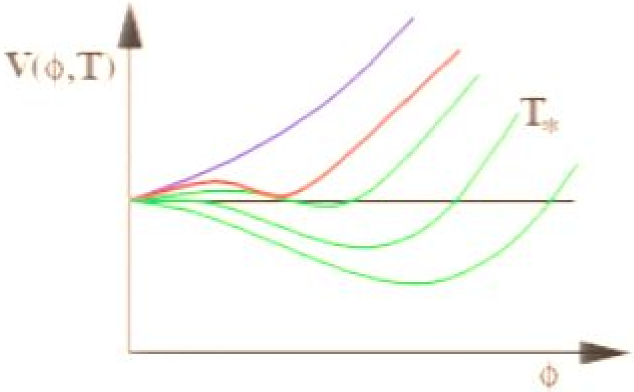
GWs from first-order phase transitions: bubble collisions and turbulence in the plasma

Via quantum tunnelling true vacuum bubbles nucleates

When bubbles collide $\Rightarrow$ emission of gravitational waves

β — bubble nucleation rate per unit volume

α — jump in energy density experienced by order parameter



EW phase transition: $T_* \simeq 300\,\mathrm{GeV}$ and $\beta/H_* \simeq 10^2$–10^3

$\Rightarrow f_{\rm peak} \simeq 10^{-8}(\beta/H_*)\,(T_*/1\mathrm{GeV}) \simeq 10^{-4}$–$5\times 10^{-3}$Hz

Intensity of GW spectrum: $h_0^2\,\Omega_{\rm GW} \simeq 10^{-6}\,(H_*/\beta)^2\,f(\alpha, v)$

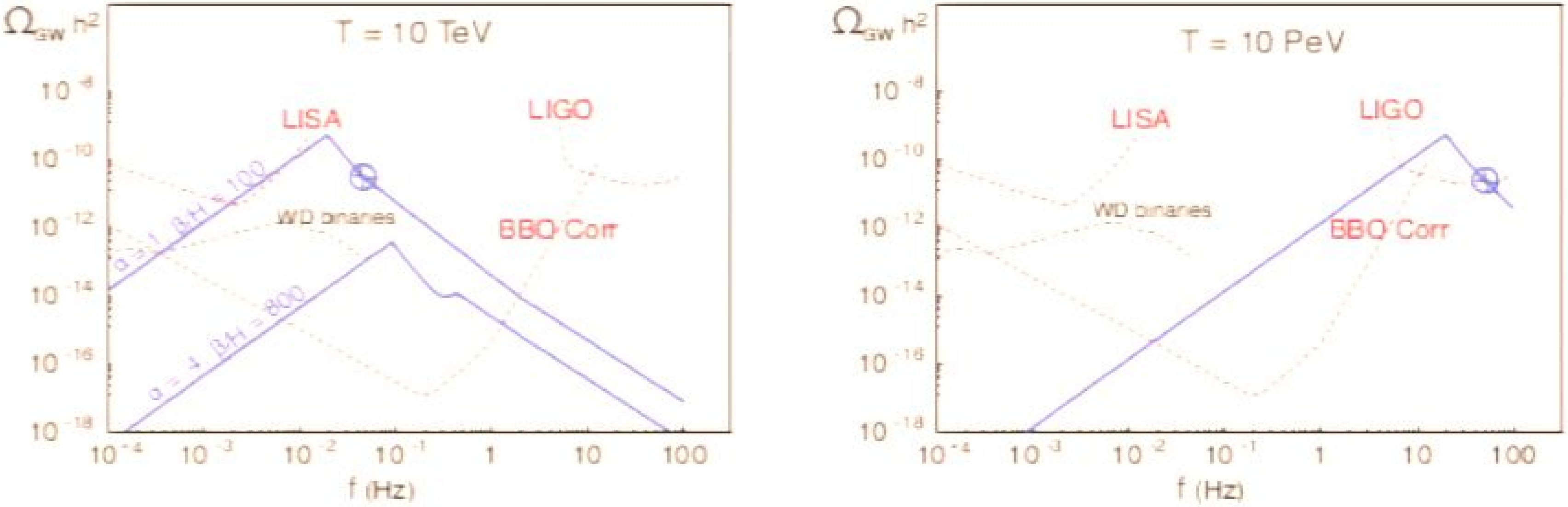
- In SM there is *no* first-order EW phase transition for Higgs mass larger then $M_{\rm W}$
- In MSSM, for certain values of Higgs mass, there are possibilities but $h_0^2\,\Omega_{\rm GW} \leq 10^{-16}$

  [Kosowsky & Turner 94; Kosowsky, Turner & Kamionkowski 94]
- In NMSSM: $h_0^2\,\Omega_{\rm GW} \;\leq\; 10^{-15}$–$10^{-10}$ with $f_{\rm peak} \simeq$ 10mHz

  [Apreda, Maggiore, Nicolis & Riotto 01; Nicolis 03] [Caprini & Durrer 06]

GW background from phase transitions at EW scale and beyond it

- EW phase transition will be probed at LHC. It depends on Higgs sector
- New models of EW symmetry-breaking recently proposed



[Grojean & Servant 06]

- For low α: turbulence and collision peaks can be well separated
- For large α: only peak of turbulence is visible

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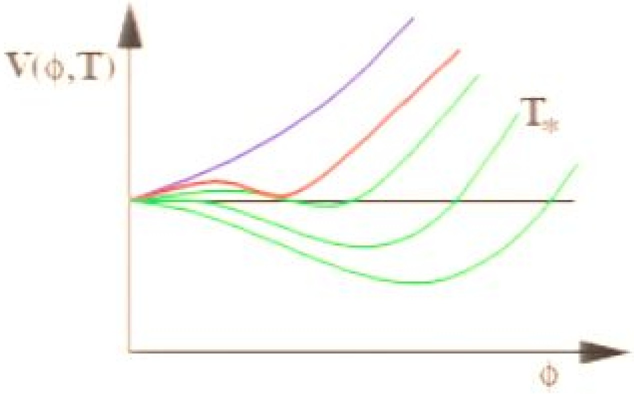

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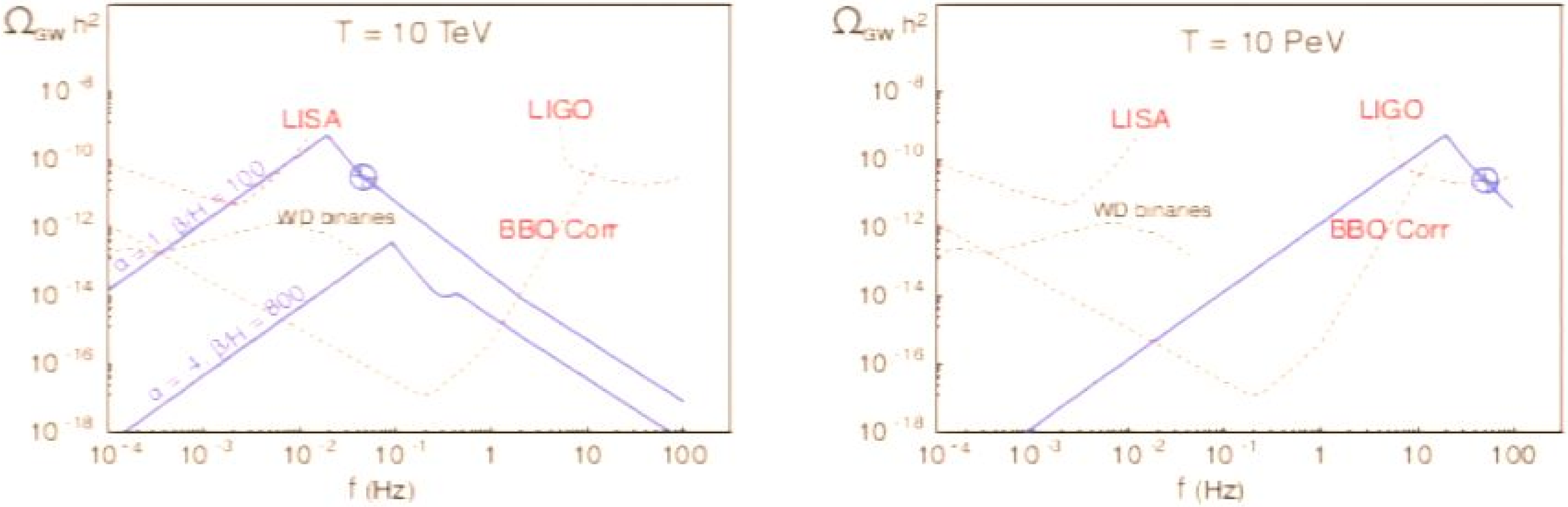

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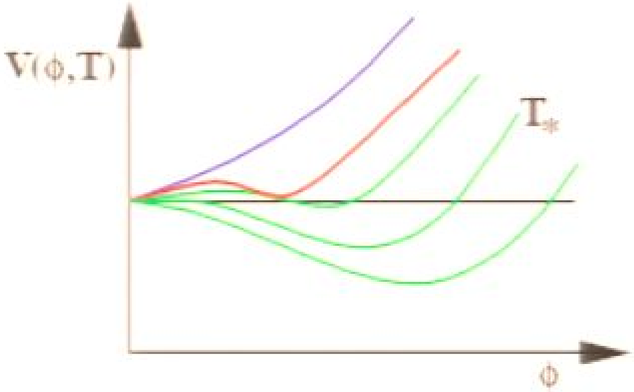

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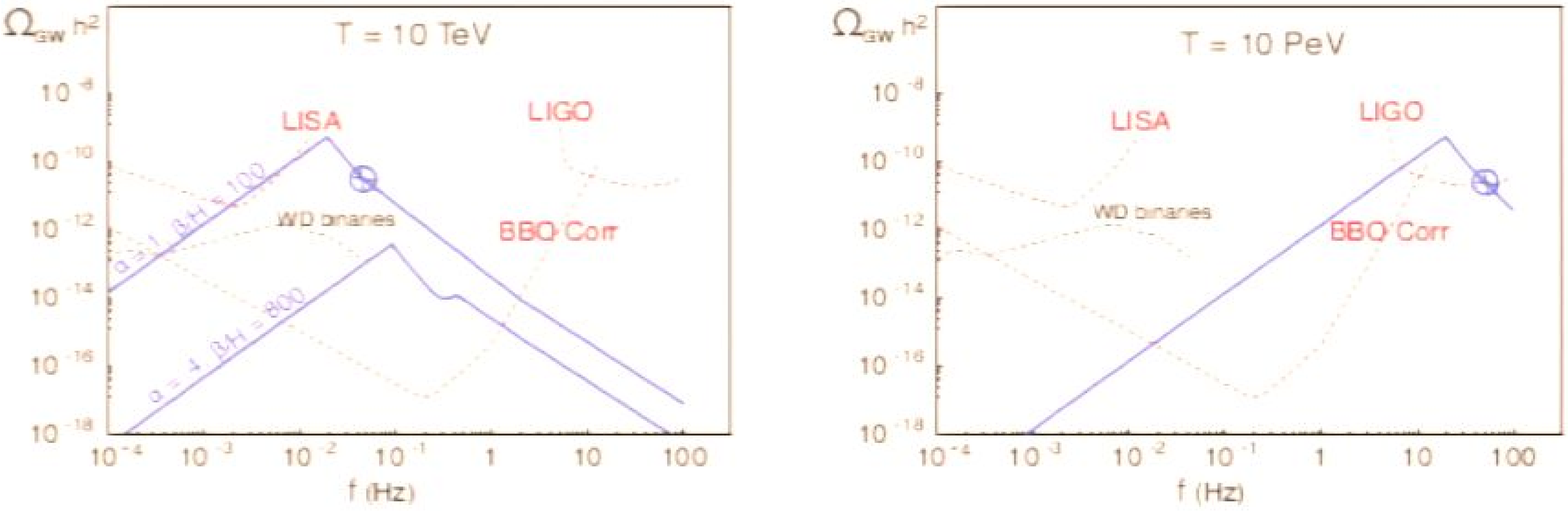

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GWs from (vibrating) cosmic string

Formed at symmetry-breaking phase transitions or in collisions of branes

- Cosmic strings have large tension (mass-per-unit length) μ, e.g., if formed at GUT scale $\mu \sim 10^{22} \mathrm{g/cm}$; they oscillate relativistically and emit GWs `[Vilenkin 81]`
- Small loops (smaller than Hubble radius) oscillate, emit GWs and disappear, but are replaced by small loops broken off very long loops (longer than Hubble radius)

r — characteristic loop's radius τ — oscillation period ($\tau \sim r$)

Quadrupole moment $Q \sim \mu\, r^3$

Loop radiates with power: $dE/dt = P \sim G \dddot{Q}^2 \sim \Gamma\, G\, \mu^2$

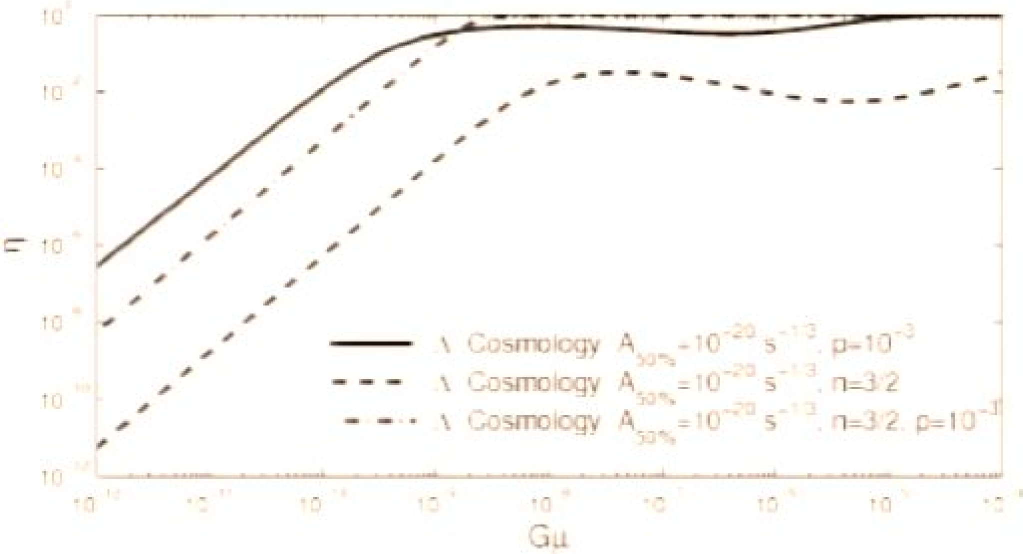
GW burst from cusps and kinks of vibrating (super)strings

The stochastic ensemble of GWs from network of oscillating loops is strongly non Gaussian and include occasional, sharp GW bursts emanating from cusps and kinks

[Berezinsky et al. 00; Damour & Vilenkin 00,01,04; Copeland et al. 04; Jackson et al. 05]

Signal detectable for a large range of values of the string tension μ reconnection probability p and loop size ϵ (and n) for cosmic (super) strings

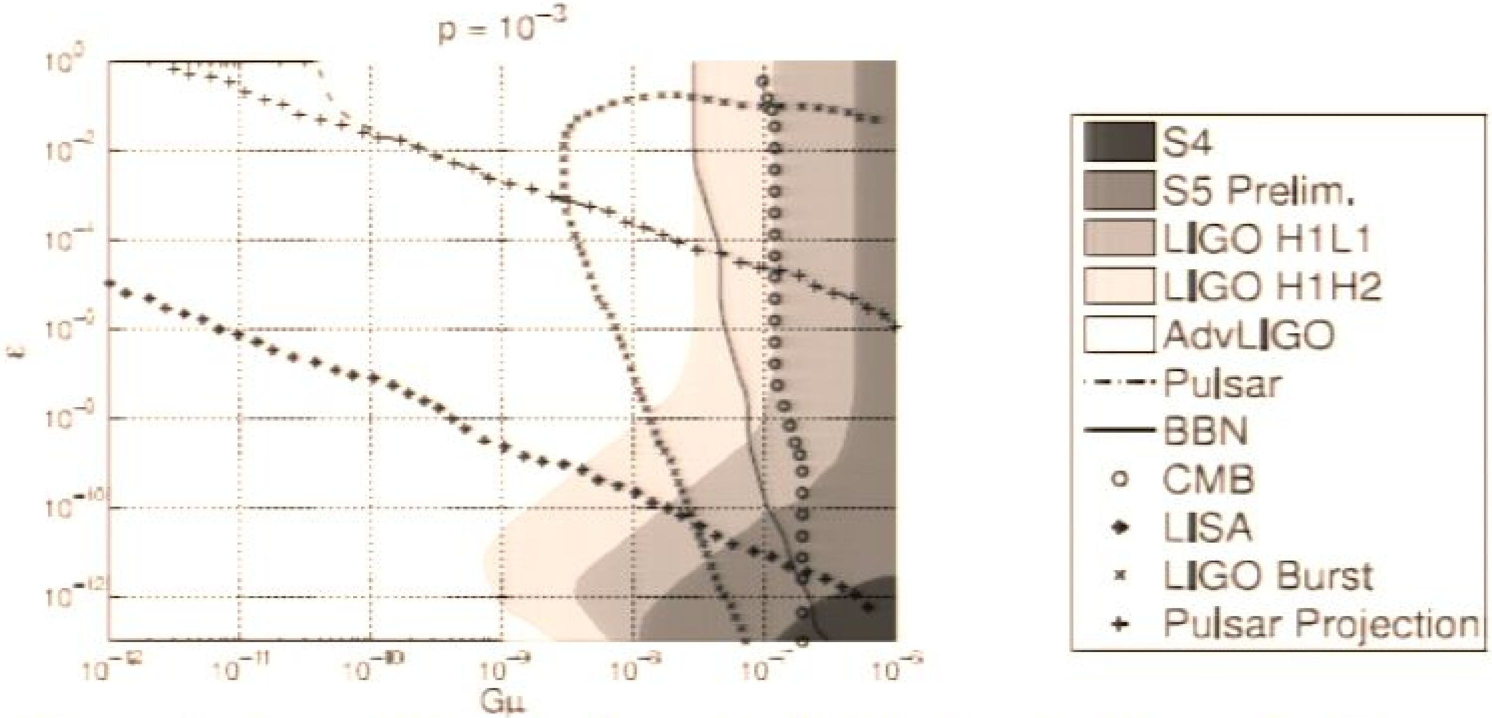
η — probability to observe at least one event in one year



at $f_{GW} = 75$Hz, optimal oriented [Siemens et al. 07]

Current and future upper limits with LIGOs

[Update from Siemens, Mandic & Creighton 07]



More robust predictions for loop size distribution in string networks are needed

Compact binaries as standard *sirens*

- Observation of gravitational radiation from inspiraling binary provides a self-calibrated absolute distance determination to the source

  [Schutz 85; Schutz & Krolak 87; Markovic 93; Finn & Chernoff 93; Finn 96]

$$h_{\rm GW}(t) \propto \frac{\mathcal{M}_z^{5/3}\,\dot{\phi}_{\rm orb}^{2/3}(t)}{D_L(z,\Omega_M,\Omega_\Lambda,\dots)}\,\mathcal{F}(\text{angles})\,\cos[2\phi_{\rm orb}(t)] \qquad \mathcal{M}_z = \mathcal{M}\,(1+z)$$

– Three ground-based interferometers or LISA itself can determine the location of the binary its parameters, the cosmological distance but not the source's redshift z!

– Redshift could be inferred from EM counterpart: GRBs for NS-NS; pre- and post-merger events for massive BH-BH $\Rightarrow$ $\delta D_L/D_L$ **decreases from** 1–10% **to** 0.15–1%

– Waves propagate through inhomogeneous Universe $\Rightarrow$ they are magnified or demagnified (weak gravitational-lensing) $\Rightarrow$ the measurement is degraded unless high event rates or lensing mass distribution is reconstructed

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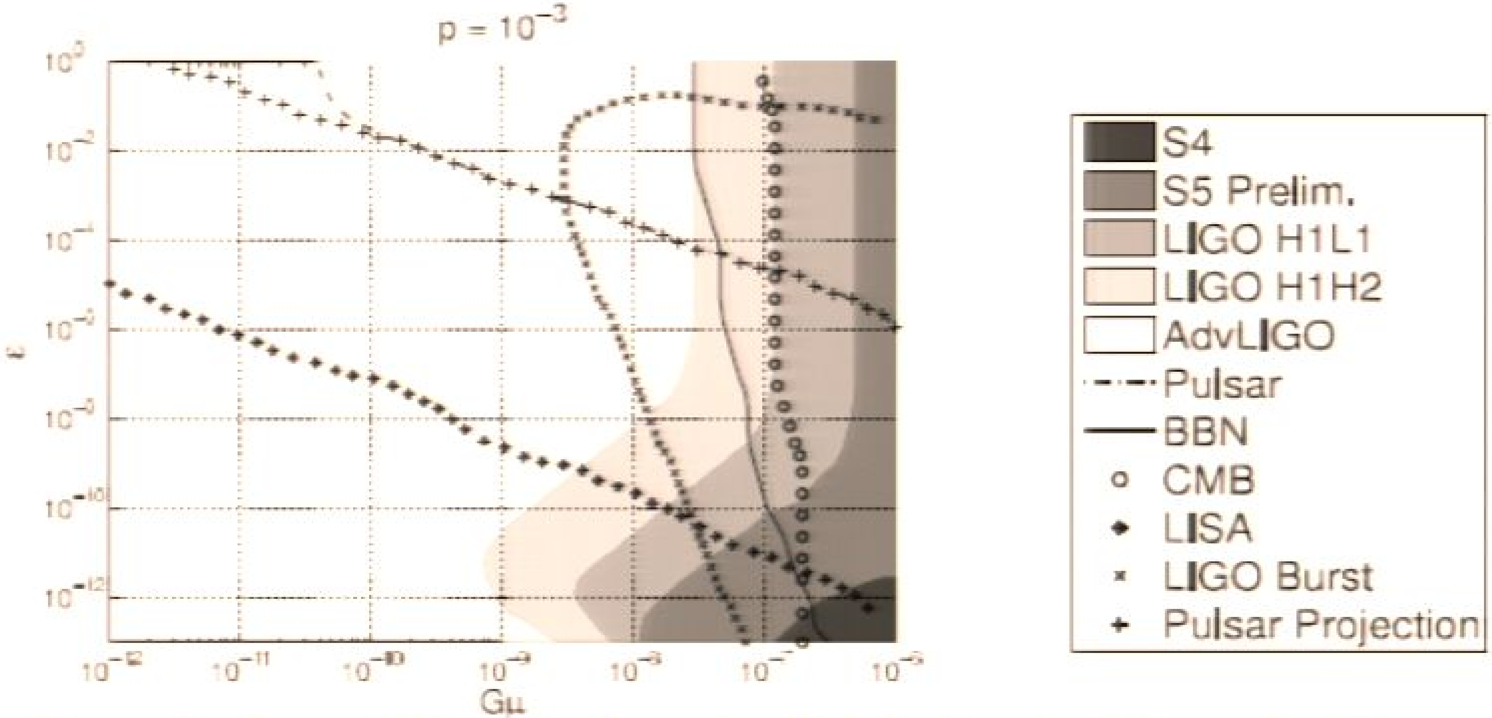

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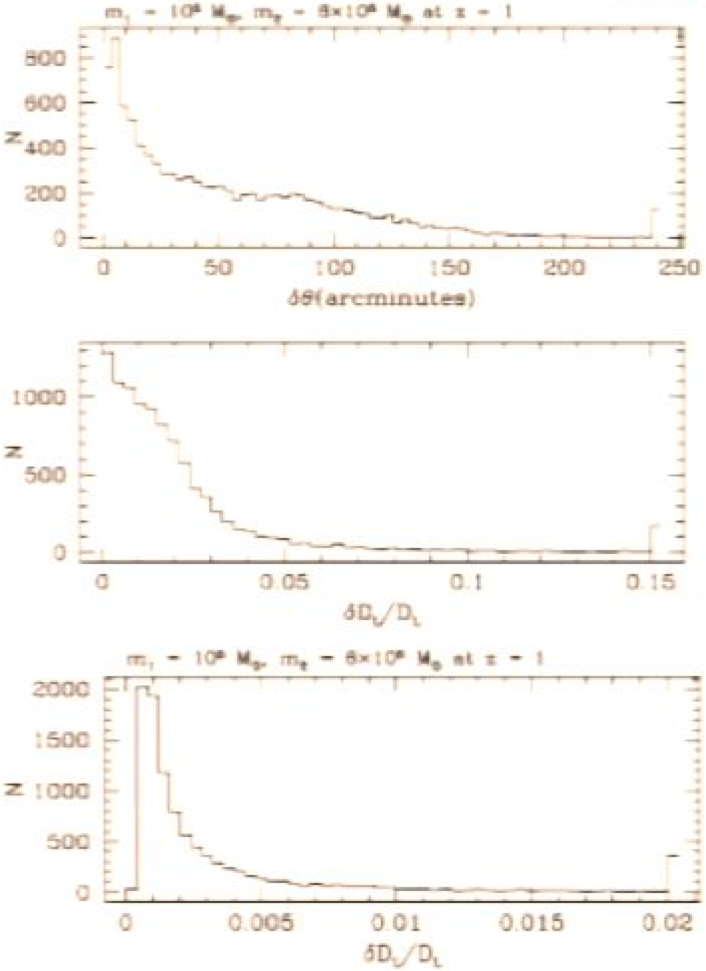
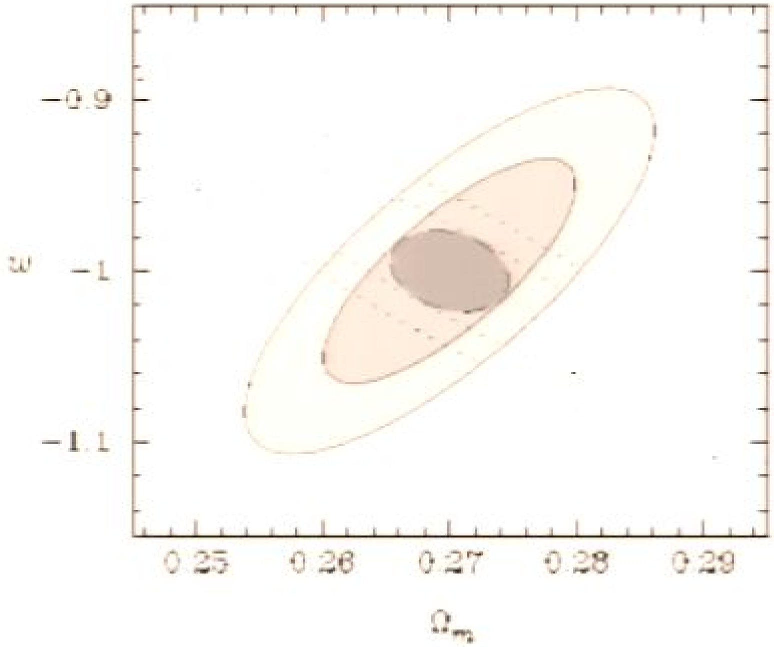
Cosmology with LISA





- solid contours: 68%, 95% confidence regions from 100 massive BH-BH between $0 < z < 2$
- dashed contours: 3000 SNe between $0.02 < z < 2$

[Dalal, Holz, Hughes & Jain 07; Holz & Hughes 06]

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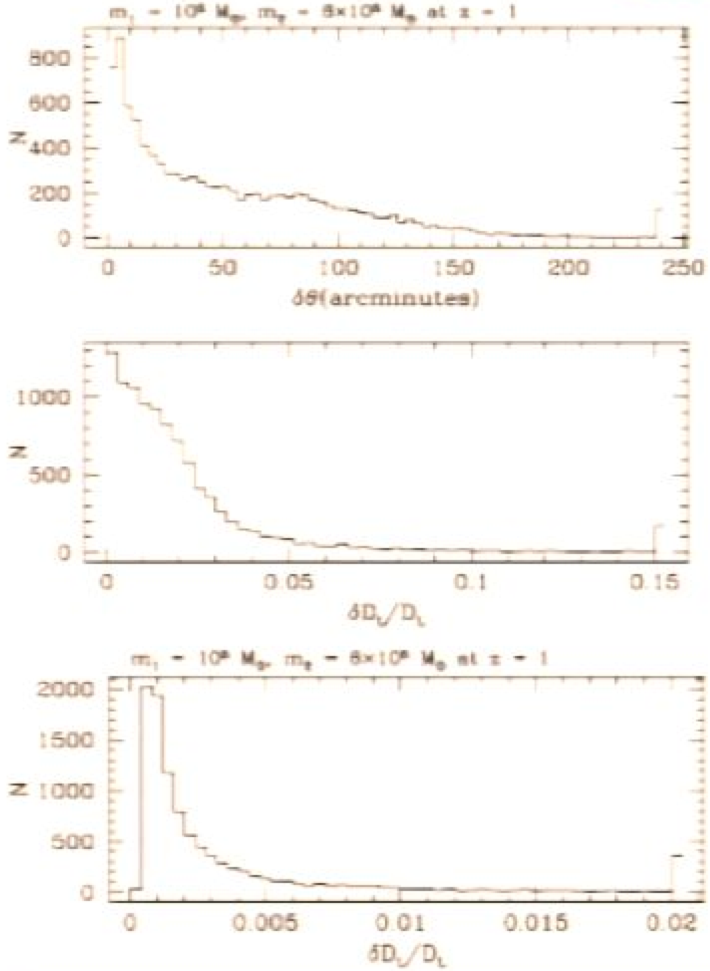

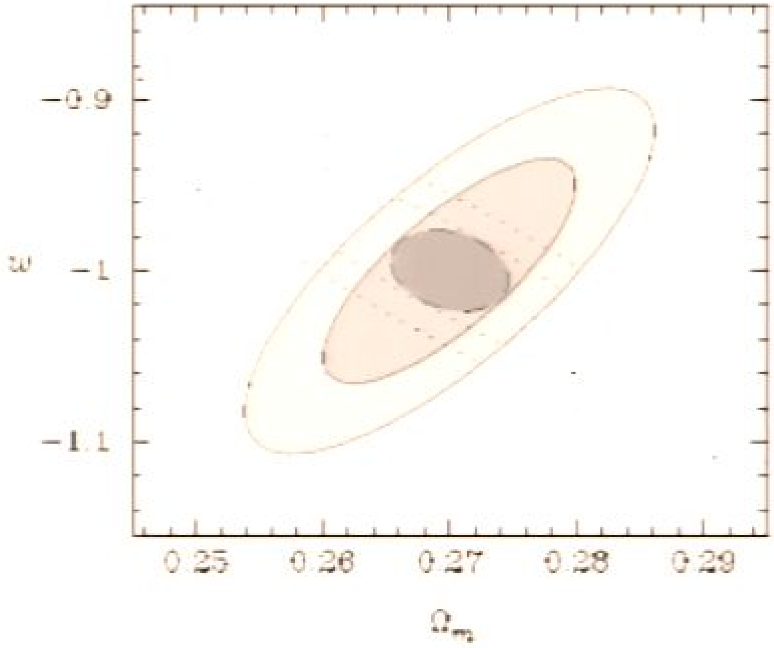

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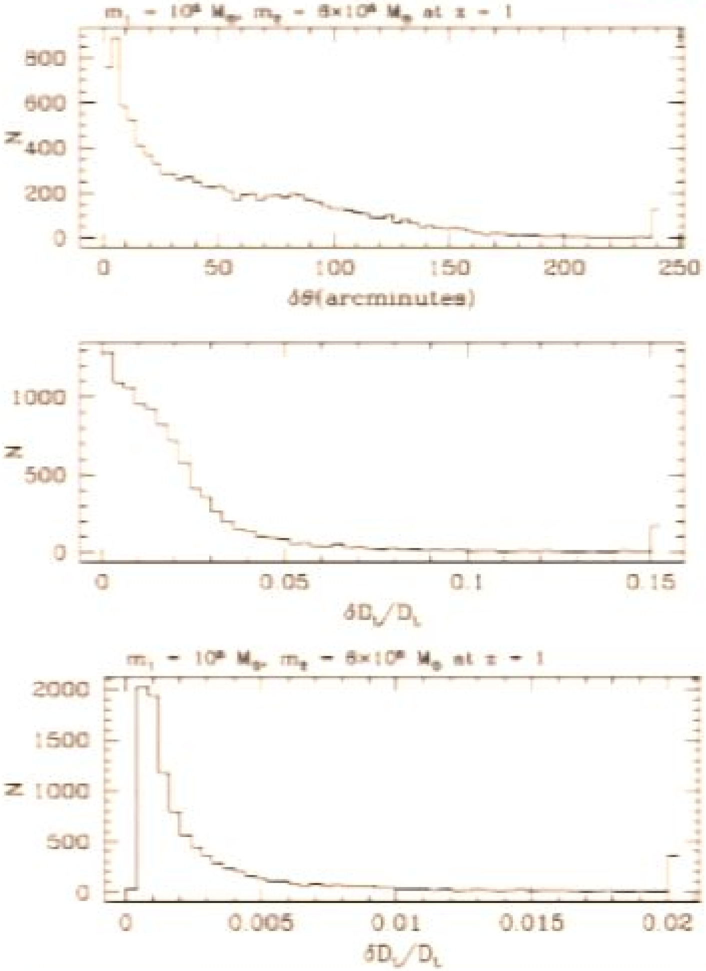

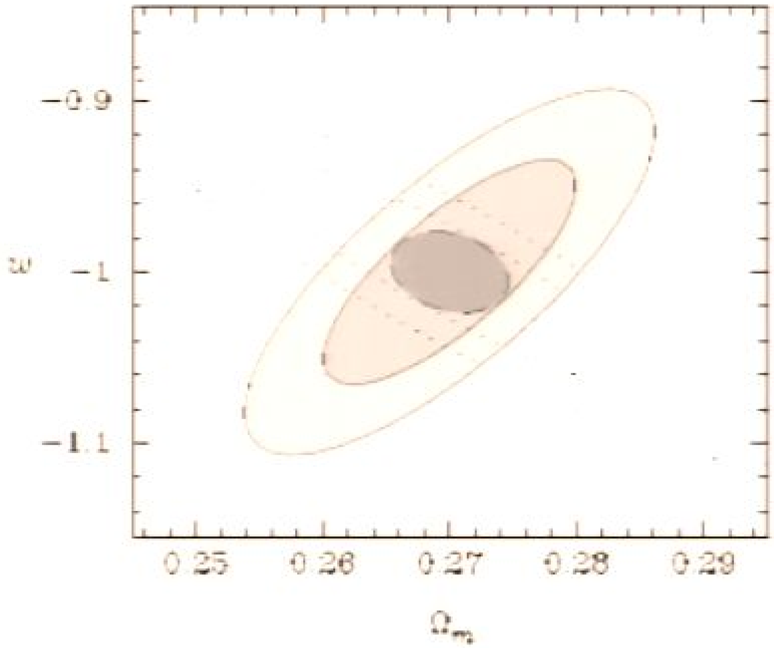

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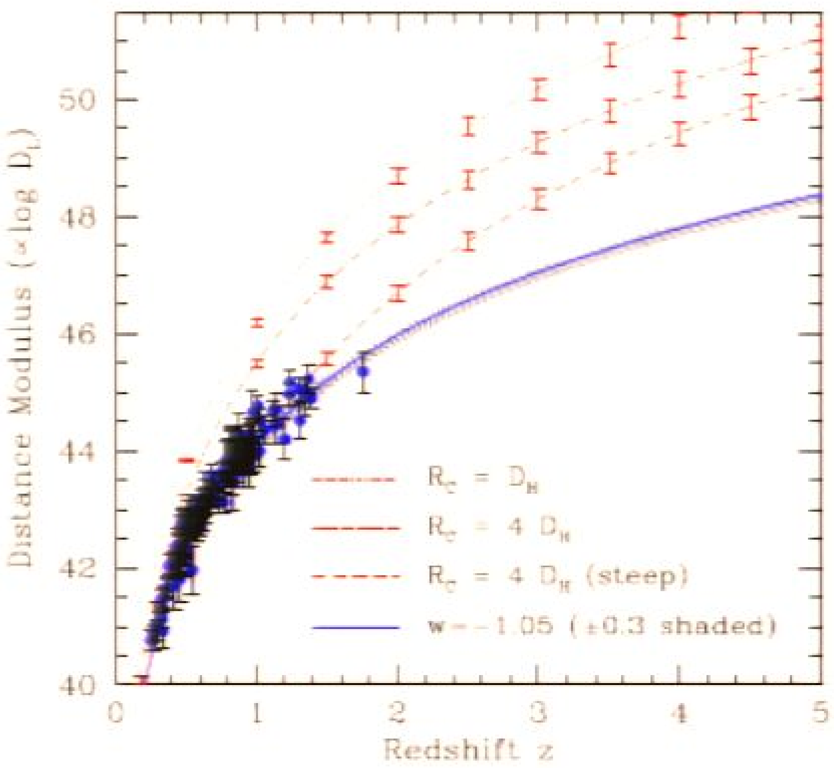
Probing gravity with spacetime sirens

- Theories with extra dimensions:
  - Gravity modifications may contain a new length scale R_c beyond which gravity deviates from GR
  - At distances $> R_c$ gravity *leaks* in extra dimensions
  - $h_{\rm GW} \propto D_L^{-({\rm dim}-2)/2}$

$\Rightarrow$ Gravitational Hubble diagram may differ from EM Hubble diagram

[Deffayet & Menou 07]



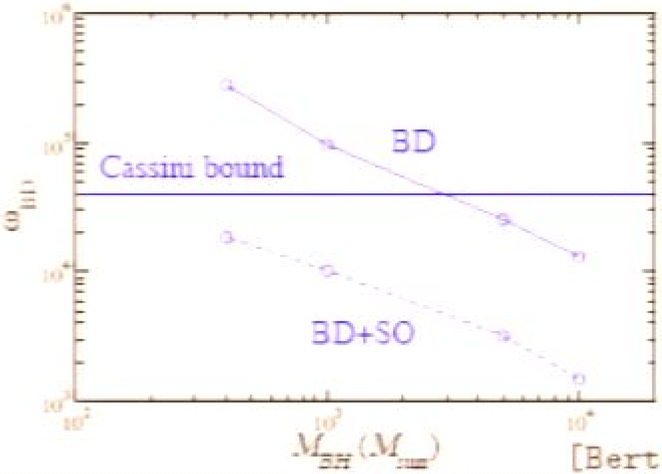
$R_c = 1$–$4 D_{\rm H} \sim 2$–8 Gpc

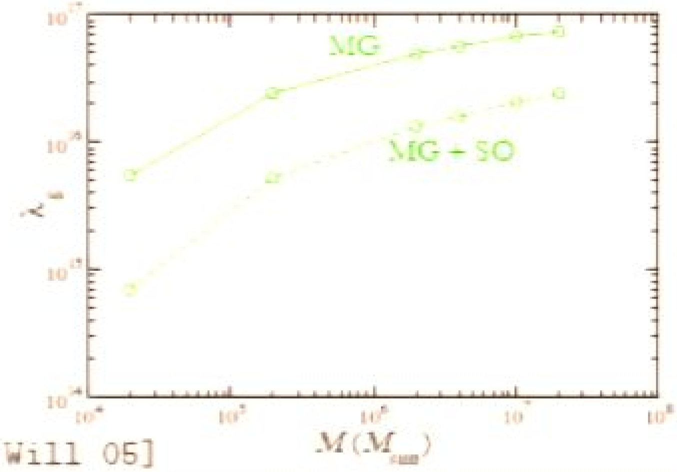
Testing alternative theories of gravity using compact binaries

[Will 94; Krolak et al. 95; Will 98; Scharre & Will 02; Will & Yunes 04, Berti, AB & Will 05]

- Scalar-tensor theories: phasing modified by GW dipole radiation
- Massive graviton theories: GW–propagation-speed depends on wavelength $\Rightarrow$ distortion in time of arrival with respect to GR

$$\dot{\omega} = \frac{96}{5\mathcal{M}^2}(\mathcal{M}\omega)^{11/3}\left\{1 + \frac{5\,\bar{\alpha}^2\,\eta^{2/5}}{192\,\omega_{\rm BD}}(\mathcal{M}\,\omega)^{-2/3} + \frac{96\,\pi^2\,\mathcal{M}\,D}{5\,(1+z)\,\lambda_g^2}(\mathcal{M}\omega)^{2/3} + \text{PN corr.}\right\}$$





[Berti, AB & Will 05]

Summary

- Relic GWs at large and small wavelengths can carry information on otherwise unexplored physics between $\sim 10^2$ GeV and $\sim 10^{16}$ GeV.
- Current direct-detection experiments, such as LIGOs, have approached the BBN bound and have started exploring interesting regions of parameter space.
- Possibility of constraining (or detecting) the presence of a *stiff* energy component prior to BBN.
- If CMB experiments detect a non-zero $r \Rightarrow$ upper bound on w during dark age.
- More robust predictions from string networks are needed to infer the properties of cosmic (super)strings from observations.
- Compact binaries as standard sirens $\Rightarrow$ tests of gravity and cosmology.
- In some frequency bands, cosmological signals compete with astrophysical ones.